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Seismic behavior of hybrid fiber reinforced cementitious composite beam–column joints

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ABSTRACT

This paper presents the experimental results of six exterior beam–column joints with different concrete composites under cyclic loading. Engineered cementitious composite with polypropylene fiber and hybrid cementitious composites (HCC) using three different types of fiber namely hooked end steel fiber; brass coated steel fiber and polypropylene fiber are explored in this study. The hysteresis behavior, ductility response, energy dissipation with damping characteristics, crack patterns and damage index of all tested specimens are analyzed and compared with the cyclic response of conventional specimens. The test results indicate that HCC increases load carrying capacity and enhances energy dissipation with increased stiffness retention over conventional specimens. At higher rotation, joint specimens with HCC manifest better damage tolerance capacity over conventional specimens. This investigation implies that the use of HCC in the joint region may be an alternative solution to significantly increase the shear capacity, damage tolerance capacity and member ductility.

1. Introduction

In reinforced concrete framed structure the forces from column and adjacent beam are transferred through the beam–column joints. These joints are subjected to compressive, tensile and shear forces and the accumulation of these combined forces makes the joints the most vulnerable part of moment resisting frame (MRF) buildings under earthquake loading. The joint resisting capacity against these forces depends upon the diagonal strut and truss mechanisms composed by the combined action of longitudinal and shear reinforcement [1,2]. Generally these joints are expected to carry significant load without loss during inelastic deformation under earthquake loading. But under the cyclic nature of earthquake loading, the joints fail in shear with spalling of concrete and loss of bond between the embedded reinforcement and concrete matrix. In fact the brittle nature of concrete seems to be ineffective in restricting the shear crack formation, and responsible for the early slippage of embedded beam bar from the joint during flexural yielding of reinforcement.

The addition of closely spaced transverse reinforcement in the joint region is the conventional way to enhance the seismic performance of the joints. The conventional confinement leads to steel congestion with problems in concrete compaction. The brittle nature of concrete improves by the confinement of transverse reinforcement results in achieving partial ductile behavior. The addition of discontinuous steel fiber in concrete enhances the tensile strain capacity by the bridging action of steel fiber as compared to conventional concrete [3–5]. But, as the deformation increases, the cracked fiber reinforced concrete (FRC) is unable to hold the stress across the cracks. Therefore, the entire performance of FRC element depends on the dispersion of fiber in the component. In reality, inefficiently located fibers become ineffective in the component for resisting tensile stresses resulting from applied loads [6]. Also the percentage of steel fiber more than 2% in concrete may lead to fiber segregation and excessive air entrainment. Thus the efficiency of steel fiber in resisting the tensile and flexural stress gets affected. From a conceptual point of view, reinforcement with fibers alone is not a highly efficient method of obtaining composite strength [6].

In the past few decades, High Performance Fiber Reinforced Cementitious Composites (HPFRCC) such as Slurry Infiltrated Fiber Reinforced Concrete (SIFCON), Engineered Cementitious Composites (ECC) with higher tensile strength and strain hardening behavior have been investigated for performance oriented structural application. In HPFRCC the absence of coarse aggregate and the high volume of fiber with proper dispersion provide strain hardening property and increase the ductility of structural component. Also the problems associated with the brittle nature of conventional concrete such as spalling of concrete, crushing and bond splitting can be overcome. The tensile strain property of HPFRCC not only enhances the matrix of post cracking behavior but also increases the interfacial bond between concrete and steel reinforcement.

In SIFCON, higher volume of steel fibers are pre-packed layer by layer in mold and then slurry is poured on the packed fiber surface with a little pressure. In ECC, minimum of 2% Poly-Vinyl Alcohol (PVA) and Poly-Ethylene (PE) fibers are used with cementitious materials to

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Table 1
Concrete mix proportions for SIFCON and ECC.

Specimen details	Cement	Sand	Coarse aggregate	Silica fume	Steel wool	Water binder ratio	Super plasticizer	Fibers
Conventional concrete	1	1.45	2.25	–	–	0.45	0.5	–
SFRC	1	1.35	2.15	–	–	0.45	0.5	Refer to table no. 2
HPFRCC mortar ratio	1	0.6	–	0.1	0.1	0.45	0.75	

make composites. Many studies have already been carried out on the mechanical properties such as compressive, tensile and shear behavior of SIFCON and ECC and the result has shown enhanced shear and ductility response over conventional FRC. The construction difficulty associated with SIFCON limits its effective application in practice. The strain-hardening behavior of ECC with more than 1% strain capacity in tension and multiple cracking properties [7] enhances the ductile behavior and damage tolerance capacity of reinforced concrete members without any construction difficulty. The tensile property of ECC has remarkable effect on crack resisting and ductility of structural components [8–10]. The application of HPFRCC on structural components eliminates the required special transverse reinforcement with higher energy dissipation and slower stiffness degradation capability [11–15]. By considering the economic aspect and the availability of Poly-Vinyl Alcohol (PVA) fiber and Poly-Ethylene (PE) fiber, this study mainly focuses on the possibility of wider application and use of composite concrete, with different types of fibers. In this study, exterior beam–column joints with different types of HPFRCC i.e. ECC, hybrid cementitious composites (HCC) are examined under cyclic loading. The load–deflection envelope behavior, hysteresis pattern, stiffness degradation, damage tolerance and energy dissipation are obtained and compared with conventional specimens.

2. Review of literature

Victor et al. [8–10] conducted many experimental and theoretical studies on ECC and its application in structural components and observed that the ECC strain hardening behavior increased the ductile behavior of this composite over conventional fiber reinforced concrete [10]. Gregor et al. [11,12] examined the effect of ECC on column members under cyclic loading and observed relatively stable inelastic deformation and large deflection response. Gregor et al. [12] evaluated intrinsic response of moment resisting frame using advanced composite materials and introduced intended deformation mechanism theoretically. Hiroshi et al. [7] investigated seismic response of ECC using reinforced concrete beam and observed better crack resisting mechanism and ductile behavior. Shannag et al. [14] retrofitted interior beam–column joints with HPFRCC jackets ($V_f = 2\%$) and observed high load carrying capacity, displacement ductility with slower stiffness degradation. Shannag et al. [15] experimentally studied the cyclic response of interior beam–column joints with HPFRCC using hooked end steel fiber and brass coated steel fiber. A better ductile and damage tolerance behavior over conventional specimens was observed. Afsin et al. [16] investigated the effect of HPFRCC using polyethylene and twisted steel fiber in precast coupling beams under cyclic loading observing higher shear strength and stiffness retention without additional transverse reinforcement. Patodi et al. [17] studied mechanical properties of steel fiber reinforced ECC with Recron 3s fiber reinforced ECC and confirmed that the Recron 3s fiber reinforced ECC enhanced behavior under tension and impact over steel fiber reinforced ECC. The post-yield behavior of ECC using Recron fiber in moment resisting frame was studied and enhanced ductile performance over steel fiber reinforced ECC was observed [18]. Malej et al. [18,19] suggested hybrid fiber engineered cementitious composites in place of mono fiber for structural application. Fang et al. [20] studied the behavior of exterior beam–column joints without stirrups using ECC in the joint zone under reverse cyclic loading and observed higher shear strength and damping property.

2.1. Research significance

Many experimental studies have been conducted to explore the effect of fiber reinforced concrete on the cyclic performance of beam–column joints. Under large deformation the inelastic performance of fiber reinforced cementitious composites (FRCC) is better than FRC because of strain hardening property. In particular few experimental studies have been carried out to examine the influence of ECC on shear behavior of beam–column joints under cyclic loading. Moreover those composites are produced using PVA and PE fibers varying from 2 to 3% in volume. More than 3% volume fiber restricts proper mixing and also affects the initial setting time. Very limited studies have been conducted on the shear behavior of joints using cementitious composites with polypropylene fiber. In polypropylene fiber reinforced composites the preferred volume of fibers varies from 2 to 3%. Also the influence of hybrid fiber reinforced cementitious composites on the shear behavior of beam–column joints is not yet investigated with different fibers. A detailed assessment of seismic performance of beam–column joints with different hybrid cementitious composites (HCC) is experimentally investigated in this study. The volume of fibers used in this study is derived from the maximum recommended volume level in literature.

3. Experimental program

This experimental study investigates the influence of different HPFRCC in beam–column joints to enhance its shear capacity and ductile behavior. A quantitative assessment is carried out using different HPFRCC on the inelastic behavior of exterior beam–column joints.

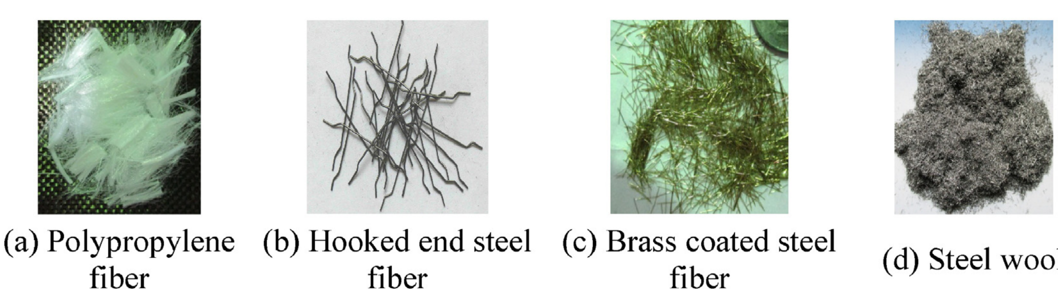

Fig. 1. Materials used in the study.